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Alexander, Jr. et al.

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(54) **METHOD AND SYSTEM FOR CREATING A RADIO FREQUENCY SIGNATURE FOR A SIGNATURE REGION IN A COVERAGE AREA OF A WIRELESS COMMUNICATION SYSTEM**

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(52) **U.S. Cl.** **455/456**; 455/457; 455/67.6; 342/457

(58) **Field of Search** 455/456, 457, 455/67.6, 67.3, 67.1, 423–425, 501, 504–506, 522, 63, 127, 226.1–226.3, 295, 296, 422; 342/457, 453, 357.1; 702/71

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Michaela C. Vanderveen; "Estimation of Parametric Channel Models in Wireless Communication Networks"; Dec. 1997; pp. 1–149.

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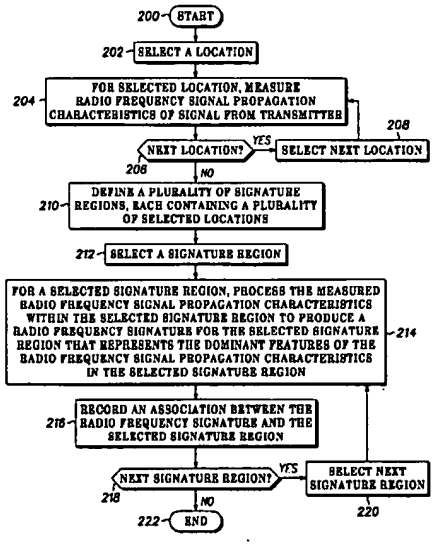
(57) **ABSTRACT**

In a wireless communication system, radio frequency signal propagation characteristics associated with a signal transmitted from several locations in the coverage area of the wireless communication system are measured. Next, a plurality of signature regions are defined in the coverage area, wherein the signature regions each contain several selected locations having selected measured radio frequency signal propagation characteristics. For a selected signature region, the associated measured radio frequency signal propagation characteristics are processed to produce a spatially averaged radio frequency signature for the selected signature region. The spatially averaged radio frequency signature represents the dominant features of the radio frequency signal propagation characteristics of a signal transmitted within the selected signature region. Finally, an association between the spatially averaged radio frequency signature and the selected signature region is recorded.

12 Claims, 8 Drawing Sheets



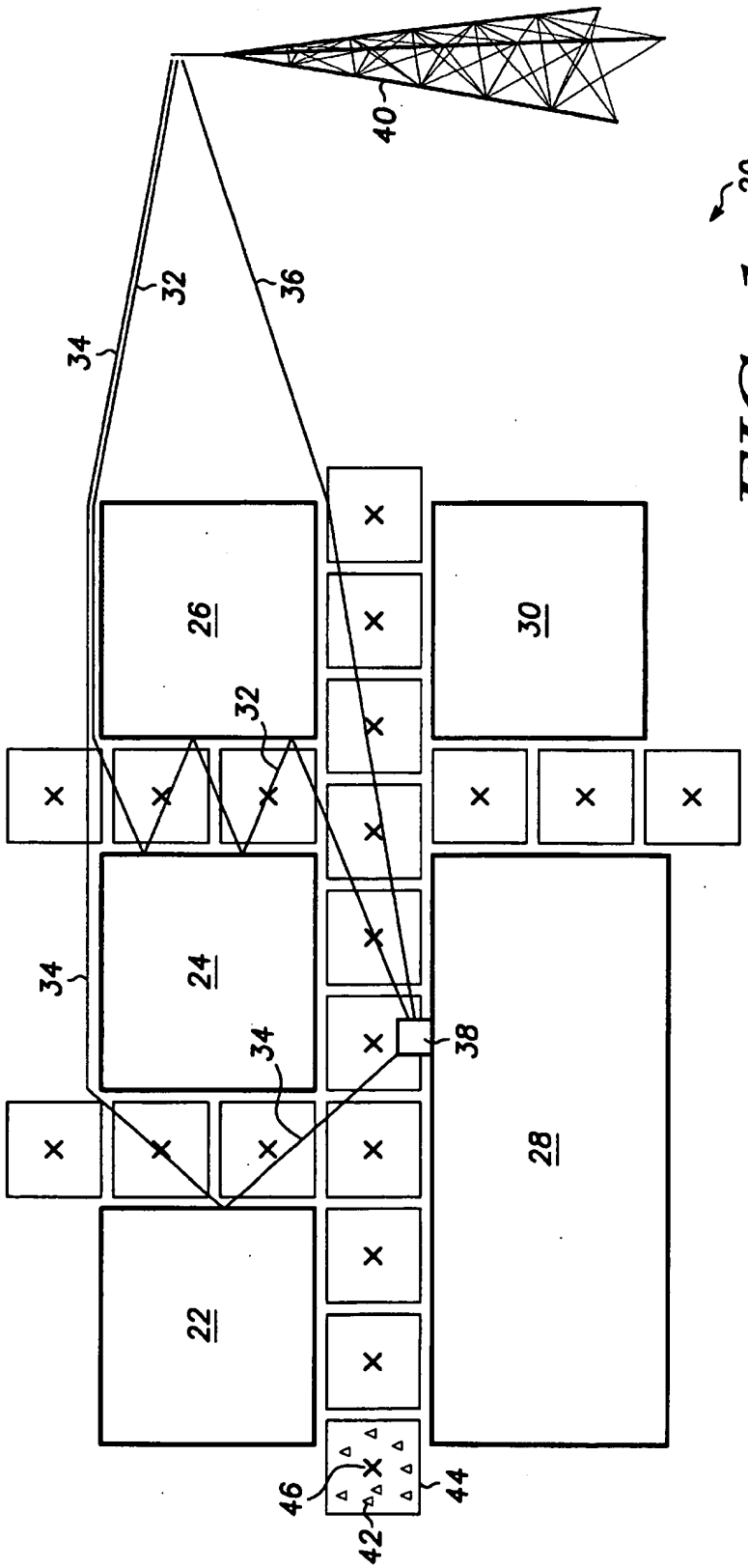


FIG. 1

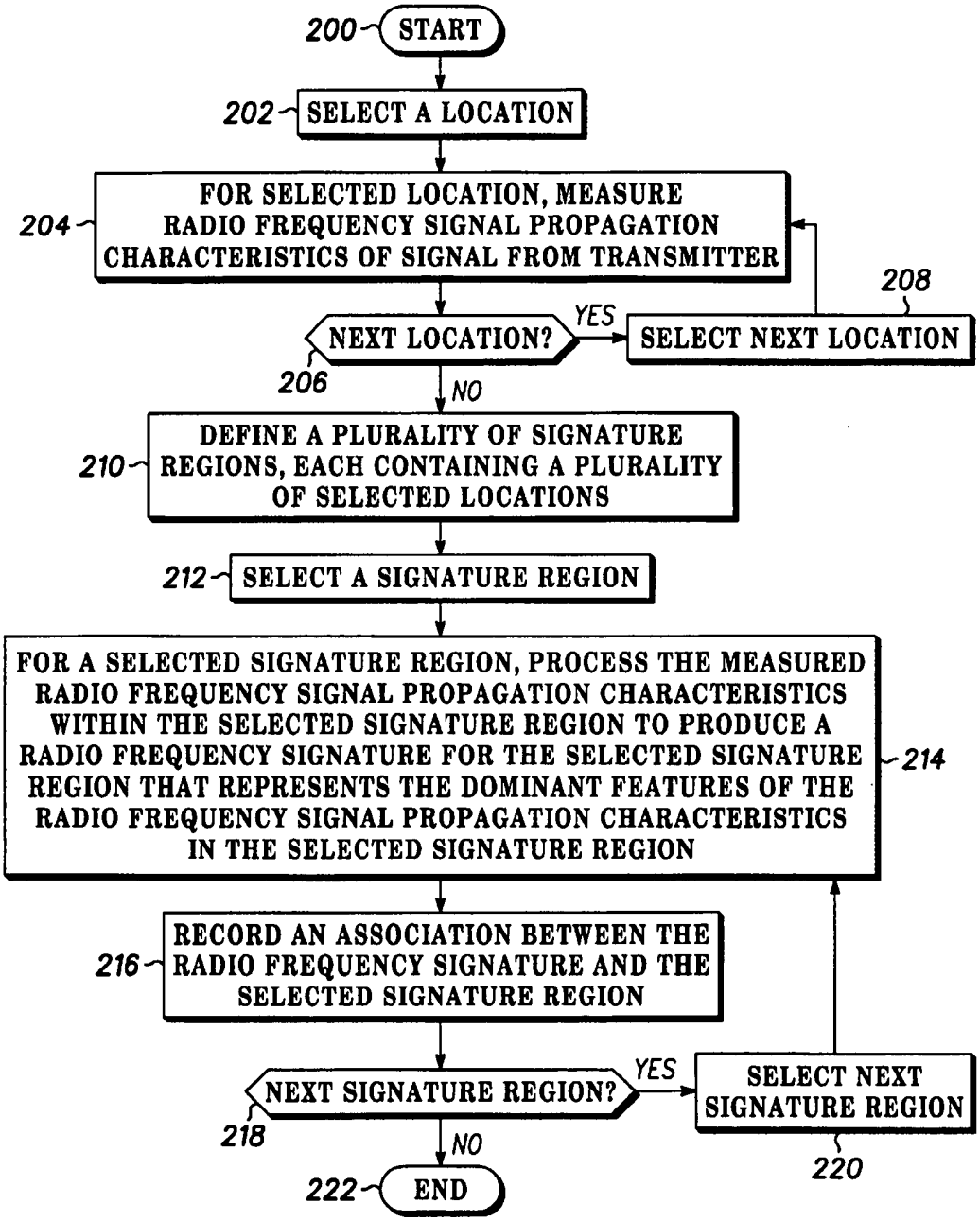

200
START
202
SELECT A LOCATION
204
FOR SELECTED LOCATION, MEASURE RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS OF SIGNAL FROM TRANSMITTER
208
NEXT LOCATION?
YES
SELECT NEXT LOCATION
206
NO
210
DEFINE A PLURALITY OF SIGNATURE REGIONS, EACH CONTAINING A PLURALITY OF SELECTED LOCATIONS
212
SELECT A SIGNATURE REGION
FOR A SELECTED SIGNATURE REGION, PROCESS THE MEASURED RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS WITHIN THE SELECTED SIGNATURE REGION TO PRODUCE A RADIO FREQUENCY SIGNATURE FOR THE SELECTED SIGNATURE REGION THAT REPRESENTS THE DOMINANT FEATURES OF THE RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS IN THE SELECTED SIGNATURE REGION
214
216
RECORD AN ASSOCIATION BETWEEN THE RADIO FREQUENCY SIGNATURE AND THE SELECTED SIGNATURE REGION
NEXT SIGNATURE REGION?
YES
SELECT NEXT SIGNATURE REGION
218
NO
220
222
END

FIG. 2

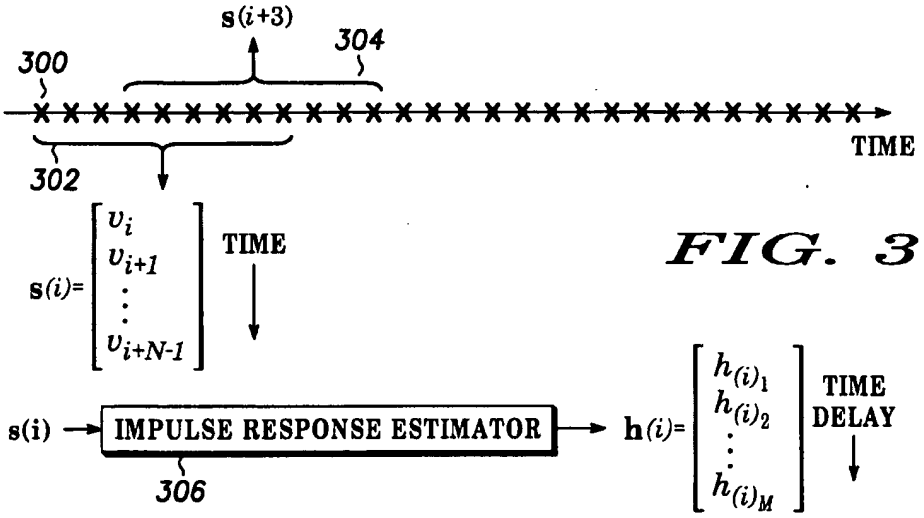

s(i+3)
304
300
TIME
302
s(i)=
v_i
v_{i+1}
v_{i+N-1}
TIME
s(i)
IMPULSE RESPONSE ESTIMATOR
306
h(i)=
$h_{(i)_1}$
$h_{(i)_2}$
$h_{(i)_M}$
TIME DELAY

FIG. 3

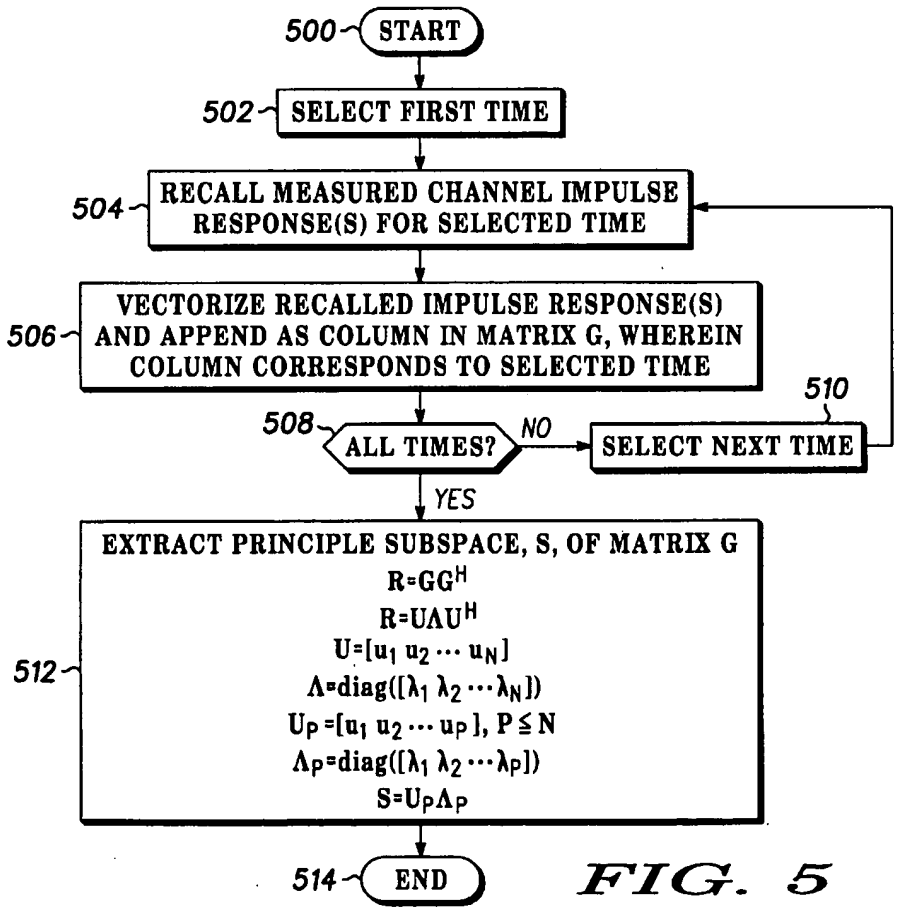

500
START
502
SELECT FIRST TIME
504
RECALL MEASURED CHANNEL IMPULSE RESPONSE(S) FOR SELECTED TIME
506
VECTORIZE RECALLED IMPULSE RESPONSE(S) AND APPEND AS COLUMN IN MATRIX G, WHEREIN COLUMN CORRESPONDS TO SELECTED TIME
508
ALL TIMES?
NO
510
SELECT NEXT TIME
YES
512
EXTRACT PRINCIPLE SUBSPACE, S, OF MATRIX G
$R=GG^H$
$R=UAU^H$
$U=[u_1\ u_2 \cdots u_N]$
$\Lambda=\mathrm{diag}([\lambda_1\ \lambda_2 \cdots \lambda_N])$
$U_P=[u_1\ u_2 \cdots u_P],\ P \leq N$
$\Lambda_P=\mathrm{diag}([\lambda_1\ \lambda_2 \cdots \lambda_P])$
$S=U_P\Lambda_P$
514
END

FIG. 5

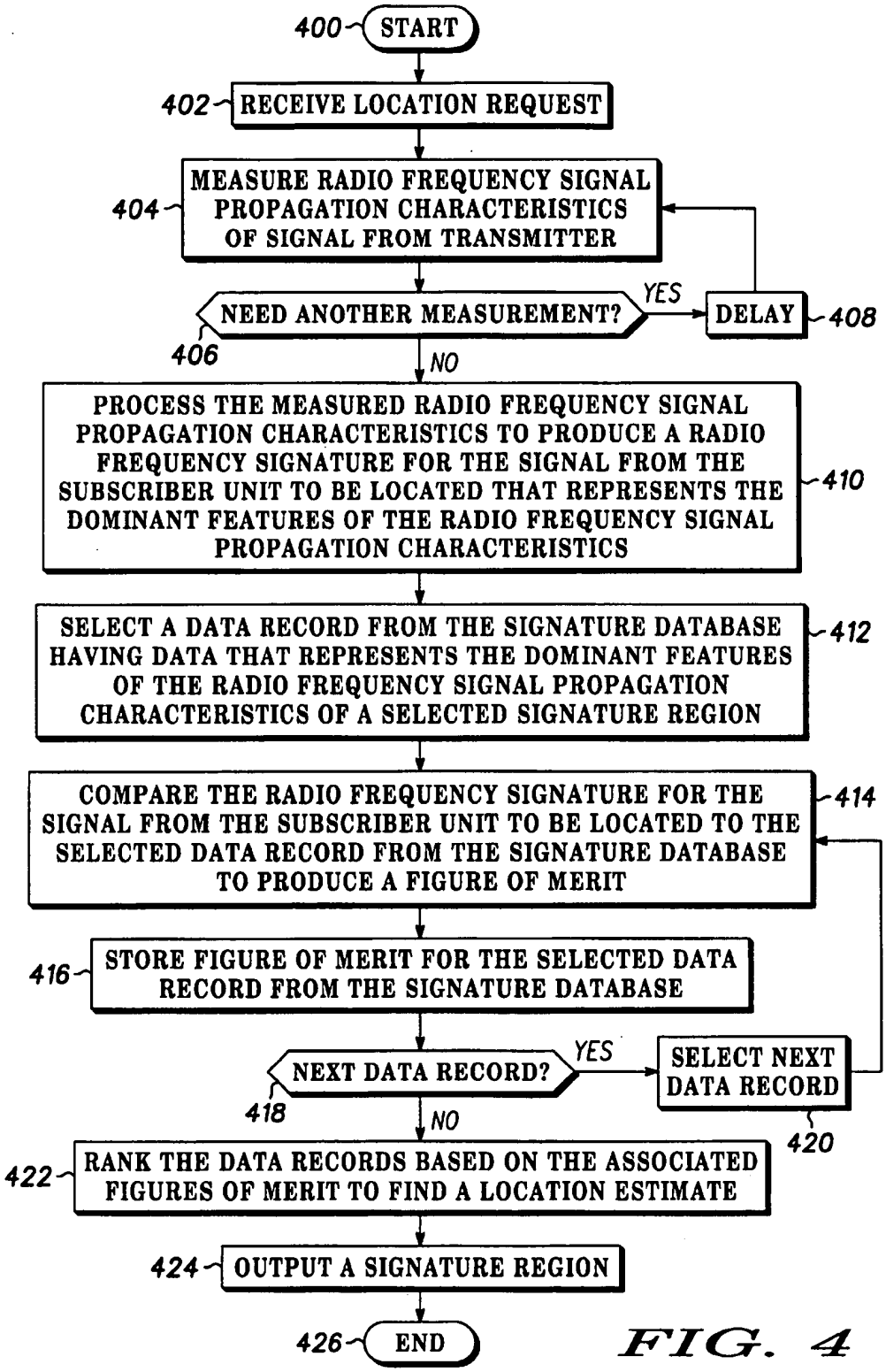

400
START
402
RECEIVE LOCATION REQUEST
404
MEASURE RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS OF SIGNAL FROM TRANSMITTER
406
NEED ANOTHER MEASUREMENT?
YES
DELAY
408
NO
410
PROCESS THE MEASURED RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS TO PRODUCE A RADIO FREQUENCY SIGNATURE FOR THE SIGNAL FROM THE SUBSCRIBER UNIT TO BE LOCATED THAT REPRESENTS THE DOMINANT FEATURES OF THE RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS
412
SELECT A DATA RECORD FROM THE SIGNATURE DATABASE HAVING DATA THAT REPRESENTS THE DOMINANT FEATURES OF THE RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS OF A SELECTED SIGNATURE REGION
414
COMPARE THE RADIO FREQUENCY SIGNATURE FOR THE SIGNAL FROM THE SUBSCRIBER UNIT TO BE LOCATED TO THE SELECTED DATA RECORD FROM THE SIGNATURE DATABASE TO PRODUCE A FIGURE OF MERIT
416
STORE FIGURE OF MERIT FOR THE SELECTED DATA RECORD FROM THE SIGNATURE DATABASE
418
NEXT DATA RECORD?
YES
SELECT NEXT DATA RECORD
420
NO
422
RANK THE DATA RECORDS BASED ON THE ASSOCIATED FIGURES OF MERIT TO FIND A LOCATION ESTIMATE
424
OUTPUT A SIGNATURE REGION
426
END

FIG. 4

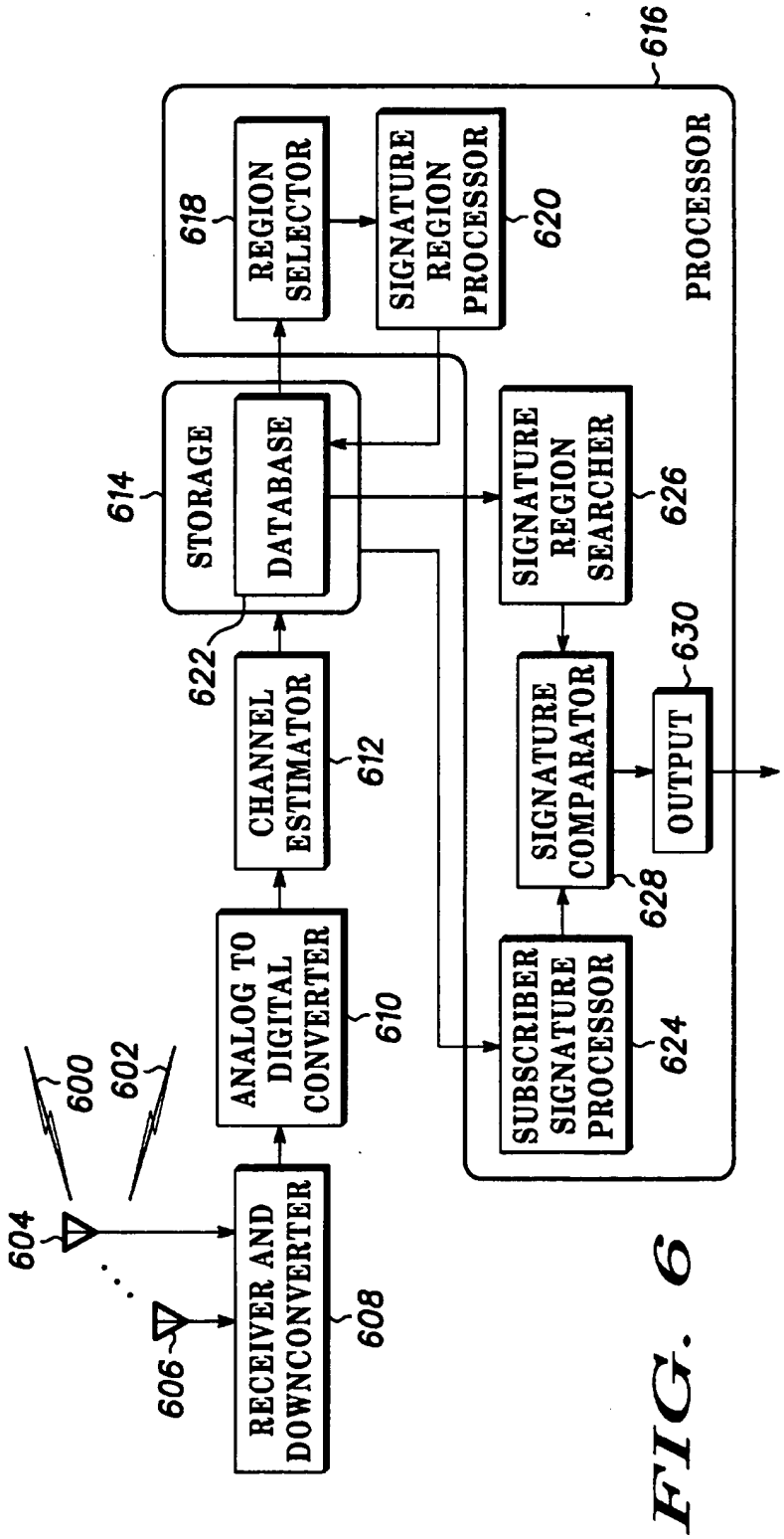

616
PROCESSOR
618
REGION SELECTOR
SIGNATURE REGION PROCESSOR
620
614
STORAGE
DATABASE
SIGNATURE REGION SEARCHER
626
622
CHANNEL ESTIMATOR
612
SIGNATURE COMPARATOR
630
OUTPUT
628
ANALOG TO DIGITAL CONVERTER
610
SUBSCRIBER SIGNATURE PROCESSOR
624
600
602
604
606
RECEIVER AND DOWNCONVERTER
608

FIG. 6

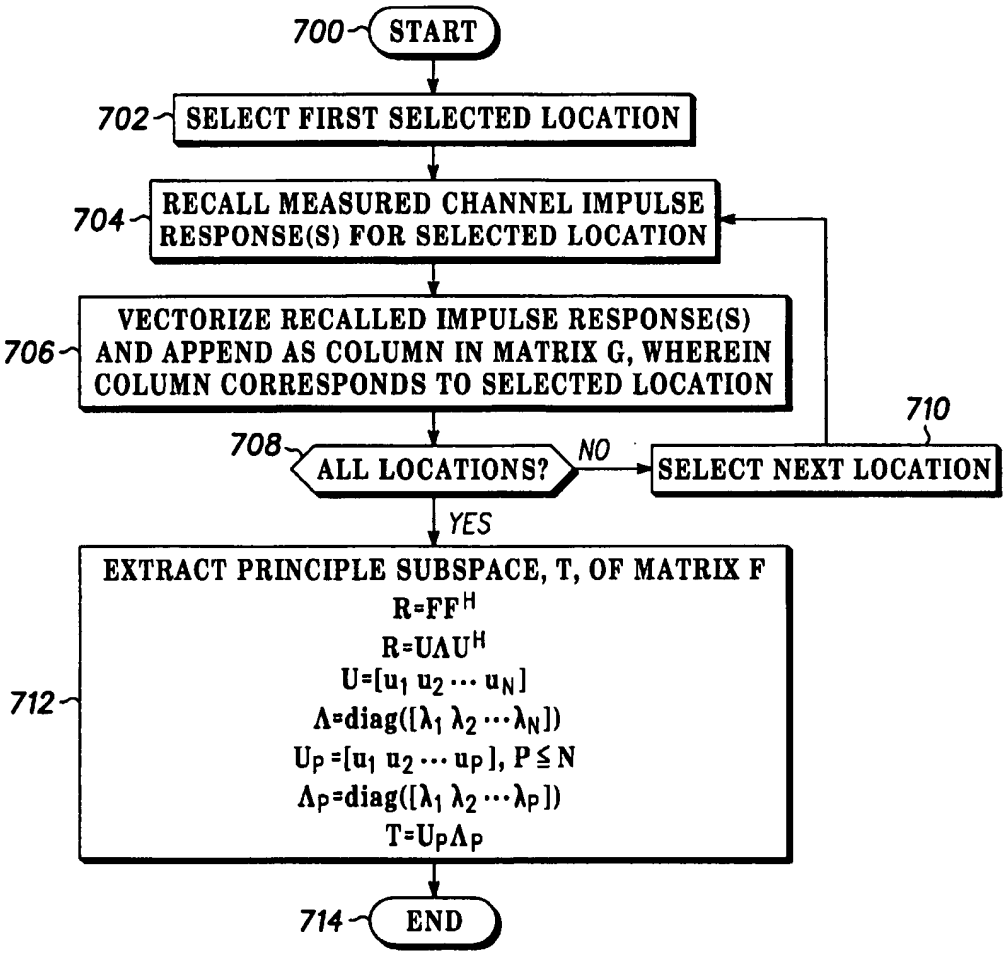

700
START
702
SELECT FIRST SELECTED LOCATION
704
RECALL MEASURED CHANNEL IMPULSE RESPONSE(S) FOR SELECTED LOCATION
706
VECTORIZE RECALLED IMPULSE RESPONSE(S) AND APPEND AS COLUMN IN MATRIX G, WHEREIN COLUMN CORRESPONDS TO SELECTED LOCATION
708
ALL LOCATIONS?
NO
710
SELECT NEXT LOCATION
YES
712
EXTRACT PRINCIPLE SUBSPACE, T, OF MATRIX F
$R=FF^H$
$R=U\Lambda U^H$
$U=[u_1\ u_2 \cdots u_N]$
$\Lambda=diag([\lambda_1\ \lambda_2 \cdots \lambda_N])$
$U_P=[u_1\ u_2 \cdots u_P]$, $P \leq N$
$\Lambda_P=diag([\lambda_1\ \lambda_2 \cdots \lambda_P])$
$T=U_P\Lambda_P$
714
END

FIG. 7

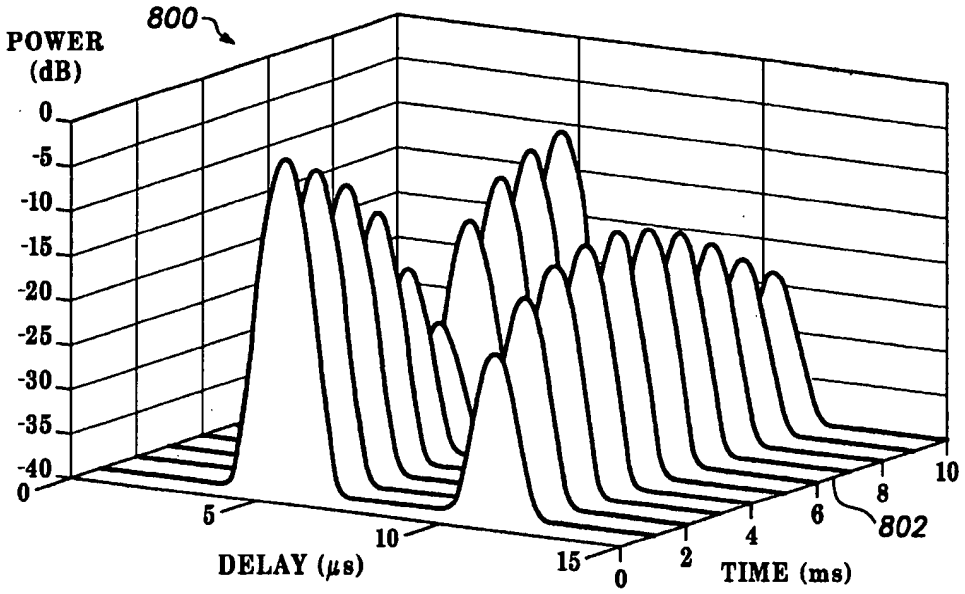

800
POWER
(dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
0
5
10
15
DELAY (μs)
0
2
4
6
8
10
TIME (ms)
802

FIG. 8

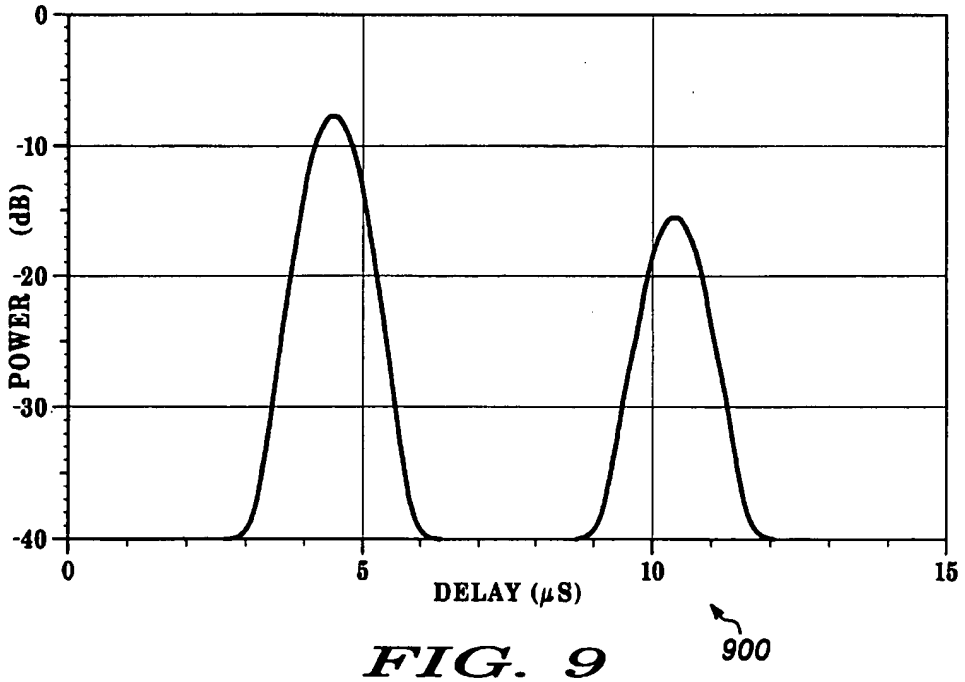

0
-10
-20
-30
-40
POWER (dB)
0
5
10
15
DELAY (μS)
900

FIG. 9

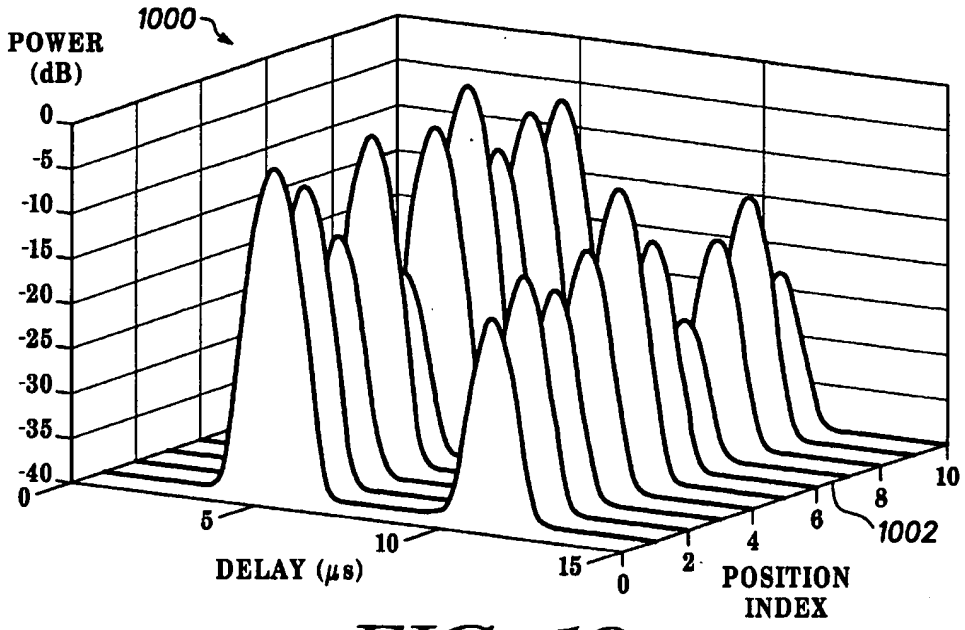

1000
POWER (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
0
5
10
15
DELAY (μs)
0
2
4
6
8
10
1002
POSITION INDEX

FIG. 10

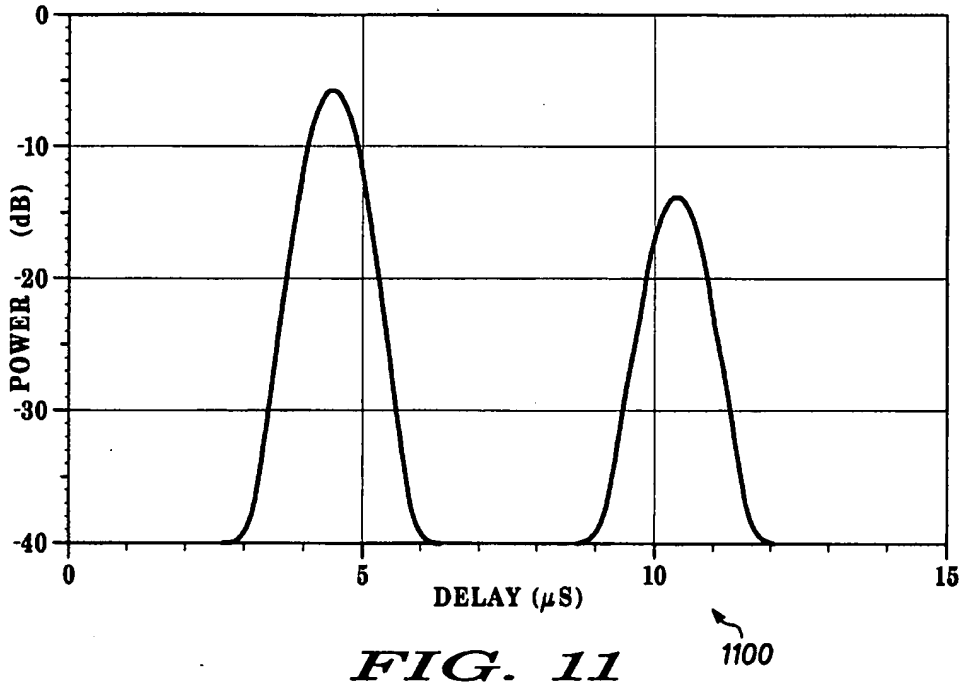

0
-10
-20
-30
-40
POWER (dB)
0
5
10
15
DELAY (μS)
1100

FIG. 11

METHOD AND SYSTEM FOR CREATING A RADIO FREQUENCY SIGNATURE FOR A SIGNATURE REGION IN A COVERAGE AREA OF A WIRELESS COMMUNICATION SYSTEM

RELATED APPLICATIONS

This application is related to application Ser. No. 09/475,095 entitled "METHOD AND SYSTEM FOR COMPARING MEASURED RADIO FREQUENCY SIGNAL PROPAGATION CHARACTERISTICS IN A WIRELESS COMMUNICATION SYSTEM," which is filed on even date herewith, and which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention is related in general to wireless communication systems, and more particularly to an improved method and system for creating a radio frequency (RF) signature for a signature region in a coverage area of a wireless communication system.

BACKGROUND OF THE INVENTION

For both users and operators of wireless communications systems it is often desirable to locate subscriber units that are making calls, or are otherwise transmitting or receiving data. Applications for technology that can locate subscribers include locating subscribers requesting 911-emergency services, assisting law enforcement agencies in various law enforcement activities, providing users with local area maps or directions, and providing users with advertising information related to the user's location.

Several technologies have been either used or proposed for providing the subscriber unit's location in a communication system, and each of these technologies has disadvantages. For example, a time difference of arrival (TDOA) system uses measurements from a plurality of base transceivers at known locations. This type of system requires signal reception of the subscriber unit's signal at more than one base transceiver, time synchronization between the base transceivers, and the measurement of line-of-sight wave front propagation, without confusing the line-of-sight signals with multipath signals, which are signals bounced and diffracted from objects affecting the propagation of the signal. The accuracy of synchronization of base transceivers in a cellular system based on interim specification 95 (IS-95), a code division multiple access (CDMA) standard, is not accurate enough to make signal propagation measurements that will provide location estimates with the desired resolution. Additionally, in a dense downtown area, also known as the urban canyon, detection of the line-of-sight wave front may not be possible because line-of-sight signal components may be shadowed or obscured by close-in multipath components.

More advanced TDOA systems use smart antennas to help eliminate some of the multipath components, enhancing detection of the prompt wave front. Smart antennas may also be able to add angle-of-arrival (AOA) measurements to the geometric equations for location finding, which further enhances performance. Unfortunately, the multipath environment of some urban canyons is too confused for smart antennas to be an effective solution. Smart antenna overlap solutions also require adding special phased array antennas to work in conjunction with the existing antennas. Service providers will most likely be reluctant to invest in additional antennas until smart antennas are needed for capacity requirements as well as location finding requirements.

Some engineers and operators propose using the global positioning system satellite system for determining a subscriber's location. This technology also has a problem in the urban canyon. In many places it is not possible to receive line-of-sight signals from a number of satellites that is needed to produce an accurate location estimate.

Other proposals include placing many microcells in an urban core area so that the subscriber's location is estimated by identifying what cell site the subscriber is using. Although microcells are gaining popularity in certain areas, the market has generally rejected microcells for capacity coverage, which means that the number of microcells deployed is probably not extensive enough to support location finding. Most current communication deployment plans still specify macrocellular coverage.

Therefore, it should be apparent that there remains a need for an improved, cost-efficient approach for locating subscriber units in a cluttered area of a communications system service area, where radio frequency signal characteristics of indirect or non-line-of-sight propagation signals are beneficially used to locate a subscriber unit. Accordingly, there is also a need for an improved method and system for creating a radio frequency signature region in a coverage area of a wireless communication system, wherein the radio frequency signature is responsive to the dominant features of radio frequency propagation characteristics of a signal transmitted from a selected signature region.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, further objects, and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings, wherein:

FIG. 1 illustrates multipath signal propagation in an urban canyon area of a wireless communication system coverage area;

FIG. 2 is a high-level logic flowchart that illustrates the method and operation of creating a spatially averaged radio frequency signatures for signature regions in a coverage area of a wireless communication system in accordance with the method and system of the present invention;

FIG. 3 depicts the processing of raw measurement data to produce an implicit measurement of radio frequency propagation characteristics in the form of a channel impulse response measurement, which measurement is used to produce database record representing a radio frequency signature in accordance with the method and system of the present invention.

FIG. 4 is a high-level logic flow chart that illustrates the method and operation of measuring a time averaged radio frequency signature for a subscriber unit in a coverage area of a wireless communication system in accordance with the method and system of the present invention;

FIG. 5 is a more detailed logic flowchart of the process of producing a spatially averaged radio frequency signature, as shown in FIG. 4;

FIG. 6 depicts a system used to create radio frequency signatures for signature regions in a coverage area of a wireless communication system, and also for measuring a radio frequency signature for a subscriber unit to be located

in a coverage area during a location event, in accordance with the method and system of the present invention;

FIG. **7** is a more detailed logic flowchart of the process of producing a spatially averaged radio frequency signature, as shown in FIG. **2**;

FIG. **8** is a graphical representation of evolving power delay profiles, which are used by the method and system of the present invention;

FIG. **9** is a graphical representation of nonlinearly averaging the data of FIG. **8**;

FIG. **10** is a graphical representation of power delay profiles collected from a plurality of locations within a signature region; and

FIG. **11** is a graphical representation of nonlinearly averaging the data of FIG. **10**.

DETAILED DESCRIPTION OF THE INVENTION

With reference now to FIG. **1**, there is depicted communications system coverage area **20**, which includes buildings **22–30** that reflect and diffract radio frequency signals that travel propagation paths **32–36** between subscriber unit **38** and base transceiver **40**.

It should be evident from FIG. **1** that propagation paths **32–34** have different times of flight and angles of arrival than propagation path **36**. Thus, if transceiver **40** measures the angle of arrival and timing information from propagating signals and uses that data to estimate the location of subscriber unit **38**, the data from propagation paths **32–36** will not coalesce to indicate a single location in communication system coverage area **20** unless signal reflections and diffractions caused by buildings **22–30** are taken into account.

With reference now to FIG. **2**, there is depicted a high-level logic flowchart that illustrates the method and operation of creating spatially averaged radio frequency signatures for signature regions in a coverage area in a wireless communication system in accordance with the present invention. As illustrated, the process begins at block **200**, and thereafter passes to block **202** wherein the process selects a location in communication system coverage area **20** (See FIG. **1**). In a preferred embodiment, this process of selecting a location includes noting the present location of a transmitter in communication system coverage area **20**. This may be accomplished by recording a location from a GPS receiver located with the transmitter, or noting the location using maps or surveying equipment. Other electronic location finding devices may also be used, such as the LORAN location finding system, operated by the United States Coast Guard. In a preferred embodiment, the selected location is one of a plurality of locations selected while driving or walking through communication system coverage area **20** while carrying a transmitter that emits a signal. Some selected locations are shown in FIG. **1** at the symbol indicated by reference numeral **42**.

After a location is selected, the process measures radio frequency signal propagation characteristics of the signal from the transmitter at the selected location, as indicated at block **204**. The measured radio frequency signal propagation characteristics may include the number of multipath components, the average power in each multipath component, the gain and phase of the antenna due to the azimuth and/or elevation angles of arrival and/or polarization of each component, the Doppler frequency of each component, and the relative time delay of each component. These characteristics may be measured explicitly by parametric decomposition of the received signal. However, in a preferred embodiment, the radio frequency signal propagation characteristics are measured implicitly by sampling, computing and recording the channel impulse responses of the particular channel between subscriber **38** and each of the one or more antennas at base transceiver **40**.

If the radio frequency signal propagation characteristics are measured explicitly, a parametric model of the channel impulse response is formed, as represented by the following equation:

$$h_e(t) = \sum_{q=1}^{Q(t)} \alpha_q(t)\Gamma_e(\theta_q(t), \varphi_q(t), \xi_q(t))\delta(t - \tau_q(t)) \qquad \text{equation 1}$$

where:

e is an index to the antenna of interest,

Q(t) represents the number of paths,

$\alpha_q(t)$ is the complex amplitude of path q,

$\Gamma_e(\theta,\phi,\xi)$ is the complex valued response of antenna e due to stimulus by a wavefront with azimuth angle θ, elevation angle ϕ, and polarization angle ξ, and

$\tau_q(t)$ is the time delay of path q.

This equation for the nonstationary impulse response can be further decomposed by exploiting relative stationarity of certain parts:

$$h(T, \tau) = \sum_{q=1}^{Q(T)} \alpha_q(T)\Gamma_e(\theta_q(T), \varphi_q(T), \xi_q(T))\delta(\tau - \tau_q(T)) \qquad \text{equation 2}$$

In equation 2, T represents time and τ represents time delay. These parameters are sufficient to characterize the location dependent multipath distortion observed by the transmitted signal. At any given time, the transmitter will occupy a location, e.g. (x(t),y(t)), for which the parameters of the measured impulse response are the radio frequency signal propagation characteristics. (Note that this description of the parametric model excludes modeling of the Doppler frequency shifts due to speed of travel through the environment. This data is implicitly contained within $\alpha_q(T)$. Doppler shifts are due to travel speed, which is only secondarily associated with position. The other parameters described are more directly correlated with the transmitter's location. However, the addition of Doppler could, in some circumstances, prove beneficial.) Implicit measurements of these characteristics are made by recording samples of the impulse responses without reduction to the fundamental parameters. For example, a vector-valued implicit measurement, $h_e(T)$, of these radio frequency signal characteristics can be represented as follows:

$$h_e(T)=[h_e(T,0)\ h_e(T,T_s)\ \ldots\ h_e(T,(N-1)T_s)]^T \qquad \text{equation 3}$$

Note that any linear transformation of the responses (e.g. Fourier transformation) yields an equally valid basis for implicit description of the radio frequency signal propagation characteristics. Certain transformations will create opportunities to limit the data to a smaller region of support, thereby discarding unimportant data and reducing the amount of data to be recorded. For example, a Fourier transformation followed by band-limiting to the frequency bins in which there is significant signal power may reduce the amount of data recorded. These transformations follow the methods of van der Veen, Vanderveen and Paulraj, "Joint Angle and Delay Estimation Using Shift-Invariance Techniques," IEEE Transactions on Signal Processing, February 1998.

In a preferred embodiment, RF signal propagation characteristics are measured implicitly by sampling voltage measurements from one or more antennas at base transceiver **40**. With reference now to FIG. **3**, a single voltage sample is shown at reference numeral **300**. Voltage samples **300** must be taken at a rate greater than the bandwidth of the signal being measured.

To calculate impulse response vector h(i), groups of voltage samples s(i), such as sample groups **302** and **304** having elements v_i–v_{i+N-1}, are input into impulse response estimator **306**. Impulse response estimator **306** delivers samples of the estimated channel impulse response, as in equation 3, and h(i) in FIG. **3**. The channel impulse response may be estimated according to the method described in "Joint Angle and Delay Estimation Using Shift-Invariance Techniques," IEEE Transactions on Signal Processing, February 1998.

In a preferred embodiment, when multiple antennas are used, an impulse response is measured for each antenna, wherein the impulse response for antenna e is denoted by $h_e(i)$. For example, if E number of antennas are used, the impulse responses for all antennas for each measurement may be arranged in matrix H(i) as shown in equation 4.

$$H(i)=[h_1(i)\ h_2(i)\ \ldots\ h_E(i)] \qquad \text{equation 4}$$

After the radio frequency signal propagation characteristics are measured, the process determines whether or not there is a next location to measure in the communication system coverage area, as depicted at decision block **206**. If there is another location to measure, the process passes to block **208**, wherein the next location is selected. After selecting the next location, new measurements are taken, as described above with reference to block **204**. Note that the selected locations need not be unique, which might be the case if one drives or walks through an intersection in the coverage area twice. Even though more than one impulse response vector may be stored for the same selected location, several different locations should be selected within a signature region.

If, as determined at block **206**, all locations have been measured, the process then defines a plurality of signature regions, wherein each signature region contains a plurality of selected locations, as illustrated at block **210**. In a preferred embodiment, the selected signature regions are adjacent to each other, and are geometrically similar in shape and size, so that the regions look like a grid of tiles laid over the communications system coverage area. As an example, signature region **44** in FIG. **1** contains a plurality of selected locations **42** from which RF signal propagation characteristics have been measured.

In an alternative embodiment, signature regions **44** may be selected based upon local correlations observed in the channel impulse responses as determined by comparing a measurement at one location with a measurement at another, or by comparing a group of measurements with another group of measurements. By performing this analysis in the defining of signature regions, irregularly shaped signature regions may be formed, and those signature regions may more accurately represent radio frequency propagation characteristics from the region, which in turn will make location estimation more accurate.

Once the signature regions are defined, the process selects a first signature region, as depicted at block **212**. For the selected signature region, each of the measured RF signal propagation characteristics is processed to produce a spatially averaged radio frequency signature for the signature region, as illustrated at block **214**. This spatially averaged radio frequency signature represents the dominant features of the radio frequency signal propagation characteristics of a signal transmitted from the selected signature region and received at a base transceiver, such as base transceiver **40**.

This process of calculating a spatially averaged radio frequency signature for implicitly measured RF signal propagation characteristics may be more completely understood with reference to FIG. **7**.

In FIG. **7**, the process of calculating a spatially averaged radio frequency signature for the selected signature region from implicitly measured radio frequency signal propagation characteristics begins at block **700** and thereafter passes to block **702**, wherein the process selects a first location within the selected signature region where radio frequency signal propagation characteristics were measured.

Next, the process recalls the measured channel impulse responses for the selected location, as illustrated at block **704**. These channel responses are preferably represented as vectors that are associated with the location at which they were collected. If more than one antenna is measured, the impulse responses are recalled as a matrix with each column representing the impulse response from a single antenna, as shown in equation 4.

Next, the process vectorizes the recalled impulse responses and appends the resulting vector as a column in matrix F, wherein the column corresponds to the selected location, as depicted at block **706**. Note that the vectorizing process is only necessary if more than one antenna is used at the base transceiver to measure channel impulse responses. For L measurement locations, the matrix F can be represented as follows:

$$f(i)=\mathrm{vec}\{H(i)\}$$

$$F=[f(1)\ f(2)\ \ldots\ f(L)]$$

Next, the process determines whether or not all the measured impulse responses for the measured locations within the selected signature region have been appended in matrix F, as illustrated at block **708**. If the responses from all the locations have not been recalled and vectorized, the process selects the next location, as depicted at block **710**, and returns to block **704** to recall the next measured channel impulse response.

If the process determines at block **708** that all data has been recalled and appended to form matrix F, the process continues at block **712**, wherein principle subspace T is extracted from matrix F. This principle subspace extraction is generally accomplished by partitioning the result of either a singular value decomposition operating directly on matrix F, or by an eigendecomposition operating on a sample covariance matrix estimated from data matrix F. The partitioning separates significant terms from less important terms that may be heavily distorted by noise or other artifacts. This partitioning may be simply accomplished by ranking the computed singular values or eigenvalues in order of their magnitude, and selecting the $P \leqq N$ largest values from the group of N values, or components may be selected that exceed a threshold value. More sophisticated methods of determining the principle subspace rank are well known in the literature, e.g. as described in Simon Haykin, ed., *Advances in Spectrum Analysis and Array Processing, Vol. III*, Prentice Hall, 1995, pp.5–9 and pp. 21–23.

After the step represented at block **712** has been completed, matrix T becomes the spatially averaged RF signature for the selected signature region. Thus, the process of producing a radio frequency signature for the selected signature region from implicitly measured radio frequency signal propagation characteristics ends at block **714**.

The process described in relation to FIG. **7** is one that extracts a principle subspace from implicitly measured radio frequency propagation characteristics. For a more complete discussion of principle subspace extraction on implicitly measured radio frequency propagation characteristics, along with other methods of extracting principle subspace, see the dissertation entitled: "Estimation of Parametric Channel Models in Wireless Communication Networks", by Michaela C. Vanderveen, May 1998, Stanford University.

The principal subspace extraction captures the dominant features of the RF signal propagation characteristics from the signature region. This process filters the information received and recorded implicitly in the plurality of impulse response vectors associated with the selected signature region and removes information deemed to be unimportant or less important to location finding.

An alternative method of extracting the dominant features, and one that is conceptually easier to understand, is to nonlinearly average the measured impulse responses associated with a signature region to deliver a single average power delay profile. With reference to FIG. **10**, the measured impulse responses can be converted into power delay profiles by taking the magnitude of the complex valued samples of the impulse response at each delay. Plot **1000** is a graphical representation of a collection of such power delay profiles, with power represented in decibels, delay in microseconds, and the location of each measurement loosely represented as an integer index. The collection of profiles in plot **1000** advance along location axis **1002**, wherein the offsets along location axis **1002** represent the plurality of measurements collected that lie within a selected signature region. Averaging along location axis **1002** allows us to extract the mean features, yielding an average power delay profile. With reference to FIG. **11**, plot **1100** is a graphical representation of such an average power delay profile extracted from the data of FIG. **10**. The average power delay profile can be computed per each antenna measured. The average power delay profile, like the principle subspace, can be used to represent the average or dominant features of the radio frequency signal propagation characteristics.

The dominant features of the radio frequency signal propagation characteristics will tend to be associated with the location of the transmitter and receiver. Because the base transceiver is typically stationary in a traditional wireless communications system, we can use the dominant features to identify the location of the subscriber unit.

After the spatially averaged radio frequency signature is produced for a selected signature region, the process records an association between the spatially averaged radio frequency signature and a location representing the selected signature region, as depicted at block **216**. Preferably this recording is done by writing a record in a database that associates each spatially averaged radio frequency signature with its respective signature region, as represented by a location, such as location **46** (See FIG. **1**) at the center of signature region **44**.

Next, the process determines whether or not another spatially averaged radio frequency signature needs to be calculated for another signature region in the coverage area, as illustrated at block **218**. If additional processing for another signature region is needed, the process selects the next signature region, as illustrated at block **220**, and then returns to block **214** wherein the next spatially averaged radio frequency signature is calculated.

If the process determines at block **218** that all the signature regions have been processed, the process of database formation ends, as depicted at block **222**. The database contains spatially averaged radio frequency signatures for each signature region. The spatially averaged radio frequency signatures contain information that represents the dominant radio frequency propagation characteristics for signals transmitted from the signature region, as determined by mathematically filtering less important information from the measurements from a plurality of selected locations in the signature region. The database is now ready to use to estimate a subscriber unit location, as described in detail below.

With reference now to FIG. **4**, there is depicted a high-level logic flowchart that illustrates the method and operation of measuring a time averaged radio frequency signature for a transmitter in a coverage area of a wireless communication system, comparing the time averaged radio frequency signature with a spatially averaged radio frequency signature, and in response to the comparison, generating a figure of merit in accordance with the method and system of the present invention. A collection of figures of merit can then be used to estimate the transmitter's location by deciding from which signature region the transmitter is likely to be transmitting.

As illustrated, the process begins at block **400**, and thereafter passes to block **402** wherein the process receives a request to estimate the location of a subscriber unit.

After receiving the request, the process measures the radio frequency signal propagation characteristics of a signal from the transmitter of the subscriber unit for which the system is estimating a location, as illustrated at block **404**. The measured radio frequency signal propagation characteristics may include the number of multipath components, the average power in each multipath component, the gain and phase of the antenna due to the azimuth and elevation angles of arrival and polarization of the wave front, the Doppler frequency of the wave front, and the relative time delay of the wave front. These characteristics may be measured explicitly by parametric decomposition of the received signal. However, in a preferred embodiment, the radio frequency signal propagation characteristics are measured implicitly by sampling and recording the channel impulse responses of the particular channel between the subscriber to be located and a base transceiver.

The measurement of the radio frequency signal propagation characteristics of the signal from the subscriber unit to be located is very similar to measuring the radio frequency signal propagation characteristics of a signal from a transmitter at a selected location during the formation of the spatially averaged radio frequency signature database, as illustrated at block **204** in FIG. **2**.

Once radio frequency signal propagation characteristics have been measured, the process determines whether or not another measurement is needed, as depicted at block **406**. Preferably, several measurements of RF signal propagation characteristics will be taken periodically so that a time averaged radio frequency signature for the subscriber unit to be located can be calculated. A single instantaneous measurement of the RF signal propagation characteristics may be adequate in some circumstances, but it is well known that a single sample estimator can be subject to large variations due to the underlying random processes in signal propagation. Estimating the RF signal propagation characteristics from multiple measurements uses statistical principles to mitigate the randomness and extract the average structure or dominant features of the RF signal propagation characteristics.

If another measurement is needed, the process delays, as depicted at block **408**, and then passes back to block **404**

wherein radio frequency signal propagation characteristics are measured again. The number of measurements taken may be determined by the number of periodic measurements that can be taken over a predetermined fixed interval.

If the process determines at block **406** that enough measurements have been taken, the process proceeds to block **410** wherein the measured radio frequency signal propagation characteristics are processed to produce a time averaged radio frequency signature for the signal from the subscriber unit to be located, wherein the time averaged radio frequency signature represents the dominant features of the radio frequency signal propagation characteristics. This process of calculating the time averaged radio frequency signature may be more completely understood with reference to FIG. **5**.

In FIG. **5**, the process of calculating a time averaged radio frequency signature from implicitly measured radio frequency signal propagation characteristics begins at block **500** and thereafter passes to block **502** wherein the process selects a first time at which radio frequency signal propagation characteristics were measured for the signal from the subscriber unit to be located.

Next, the process recalls the measured channel impulse responses for the selected time, as illustrated at block **504**. These channel impulse responses are preferably represented as vectors that are associated with the time at which they were collected. If more than one antenna is measured, the responses are recalled as a matrix with each column representing the impulse response from a single antenna, as in equation 4.

Next, the process vectorizes the recalled impulse responses and appends the resulting vector as a column in matrix G, wherein the column corresponds to the selected time, as depicted at block **506**. Note that the vectorizing process is only necessary if more than one antenna is used at the base transceiver to measure channel impulse responses. For L measurement times, the matrix G can be represented as follows:

$$g(i)=vec\{H(i)\}$$

$$G=[g91)\ g(2)\ \ldots\ g(L)]$$

Next, the process determines whether or not all the measured impulse responses for all the measured times have been appended in matrix G, as illustrated at block **508**. If all the times have not been recalled, vectorized, and appended into G, the process selects the next time, as depicted at block **510**, and returns to block **504** to recall the next measured channel impulse response.

If the process determines at block **508** that all data has been recalled and appended to form matrix G, the process continues at block **512**, wherein principle subspace S is extracted from matrix G. This principle subspace extraction is generally accomplished by partitioning the result of either a singular value decomposition operating directly on matrix G, or by an eigendecomposition operating on a sample covariance matrix estimated from data matrix G. The partitioning separates significant terms from less important terms, which may be heavily distorted by noise or other artifacts. This partitioning may be accomplished by ranking the computed singular values or eigenvalues in order of their magnitude, and selecting the $P \leqq N$ largest values from the group of N values. Alternatively, components may be selected that exceed a threshold value. More sophisticated methods of determining the principle subspace rank are well known in the literature, e.g. as described in Simon Haykin, ed., *Advances in Spectrum Analysis and Array Processing, Vol. III*, Prentice Hall, 1995, pp.5–9 and pp. 21–23.

After the step represented at block **512** has been completed, matrix S becomes the time averaged RF signature for the signal from the subscriber unit to be located. Thus, the process of producing a time averaged radio frequency signature from implicitly measured radio frequency signal propagation characteristics ends at block **514**.

The process described in relation to FIG. **5** is one that extracts principle subspace from implicitly measured radio frequency propagation characteristics. For more complete discussion of principle subspace extraction on implicitly measured radio frequency propagation characteristics, along with other methods of extracting principle subspace, see the dissertation entitled: "Estimation of Parametric Channel Models in Wireless Communication Networks", by Michaela C. Vanderveen, May 1998, Stanford University.

The principal subspace extraction captures the dominant features of the signal propagated from the signature region. This process filters the information received and recorded implicitly in the plurality of impulse response vectors associated with the selected signature region and removes information deemed to be unimportant or less important to location finding.

An alternative method of extracting the dominant features, and one that is conceptually easier to understand, is to nonlinearly average the measured impulse responses associated with a signature region to deliver a single average power delay profile. With reference to FIG. **8**, the measured impulse responses can be converted into power delay profiles by taking the magnitude of the complex valued samples of the impulse response at each delay. Plot **800** is a graphical representation of a collection of such power delay profiles, with power represented in decibels, delay in microseconds, and the time of measurement of each power delay profile measured in milliseconds. The collection of profiles in plot **800** advances along time axis **802**, wherein location axis **802** represents the plurality of measurements collected within a span of time. Averaging along time axis **802** allows us to extract the mean features, yielding an average power delay profile. With reference to FIG. **9**, plot **900** is a graphical representation of such an average power delay profile extracted from the data of FIG. **8**. The average power delay profile can be computed per each antenna measured. The average power delay profile, like the principle subspace, can be used to represent the average or dominant features of the radio frequency signal propagation characteristics.

The dominant features of the radio frequency signal propagation characteristics will tend to be associated with the location of the transmitter and receiver. Because the base transceiver is typically stationary in a traditional wireless communications system, we can use the dominant features to identify the location of the subscriber unit.

With reference again to FIG. **4**, after the time average radio frequency signature has been calculated at block **410**, the process selects a data record from the signature database having data that represents the dominant features of the radio frequency signal propagation characteristics of a selected signature region, as illustrated at block **412**.

The process then compares the time averaged radio frequency signature for the signal from the subscriber unit to be located to the selected data record from the signature database, which contains a spatially averaged radio frequency signature, to produce a figure of merit, as depicted at block **414**. In a preferred embodiment, where the radio frequency signatures are derived from implicit measurements, the process of computing a figure of merit may be accomplished by calculating the distance between the principle subspaces represented by the time averaged

radio frequency signature from the subscriber unit to be located and the spatially averaged radio frequency signature from the selected data record in the database. The distance computation may be performed by computing the norm of the projection of one signature onto the other. This comparison may be a weighted comparison where more important information is given more consideration.

Alternatively, for explicitly measured radio frequency signal propagation characteristics, the signatures may be hyperdimensional vectors representing the parameters of the explicit propagation model, as in equation 2, and the figure of merit representing their comparison can be the distance between spatially and temporally averaged versions of these hyperdimensional vectors, similar to the methods outlined above for implicit measurements. Note that here, as elsewhere, averaging can include traditional linear averaging, nonlinear averaging, or subspace based averaging via extraction of a principle subspace.

Next, the process stores the figure of merit associated with the selected data record from the spatially averaged radio frequency signature database, as illustrated at block **416**. Thereafter, the process determines whether or not there is another data record to compare, as depicted at block **418**. If there is another data record to compare, the process selects the next data record, as illustrated at block **420**, and then returns to block **414** to compare the two radio frequency signatures.

If the process determines that all data records have been compared, the process continues at block **422**, wherein the process ranks the data records based on the associated figures of merit in order to find a location estimate. Once the location estimate has been found, the process outputs the coordinates of a signature region that corresponds to the location estimate, as depicted at block **424**. This output may be the coordinates of a location associated with the signature region, such as the coordinates of location **46**. The process then terminates as indicated at block **426**.

With reference now to FIG. **6**, there is depicted a system used to create a radio frequency signature for a signature region in a coverage area of a wireless communication system, and also for measuring a time averaged radio frequency signature for a subscriber unit to be located in the coverage area, in accordance with a method and system of the present invention. As illustrated, a plurality of wave fronts **600** and **602** are received by antennas **604–606**. Wavefront **600–602** represent a signal from a single source that has been subjected to multipath distortion. In other words, both wave front **600** and **602** came from the same transmitter through different propagation paths.

In a typical embodiment, antennas **606–604** may be implemented with two diversity receive antennas in each of three sectors on the top of a typical cellular tower. Antennas **606–604** are coupled to receiver and down converter **608**, which translates the spectrum from radio frequency to complex valued baseband.

The output of receiver and down converter **608** is coupled to the input of analog-to-digital converter **610**, which converts the complex valued baseband signal to a stream of digital values. The stream of digital values output by analog-to-digital converter **610** is coupled to the input of channel estimator **612**. Channel estimator **612** estimates the radio frequency signal propagation characteristics of wave fronts **600–602**. These radio frequency signal propagation characteristics may include the number of multipath components, the average power in each multipath component, the gain and phase of the antenna due to the azimuth and elevation angles of arrival and polarization of the wave front, the Doppler frequency of the wave front, and the relative time delay of the wave front. As mentioned previously, these characteristics may measured explicitly by parametric decomposition of the received signal, or implicitly by estimating, sampling and recording the channel impulse responses.

The output of channel estimator **612**, whether implicit representations of radio frequency propagation characteristics or explicit measurements of these characteristics, are stored in storage **614**. This storage may be implemented with any commonly known data storage device, such as a hard disk, tape, random access memory, CD ROM, and the like.

Processor **616** is coupled to storage **614** for recalling and processing data, and storing the results of such processing. Processor **616** may be implemented with a general purpose microprocessor, a custom application specific integrated circuit, or a digital signal processor. Within processor **616** are other functional blocks which may be implemented with various combinations of hardware and software. Note also that channel estimator **612** may also be implemented in processor **616**.

With regard to a system that builds the spatially averaged radio frequency signature database, processor **616** contains region selector **618**, which recalls data stored in storage **614**, wherein the data represents measured radio frequency signal propagation characteristics of a particular signature region. Region selector **618** then passes this data to signature region processor **620**, which computes a spatially averaged radio frequency signature for a selected signature region and stores such signature in database **622**, where it is associated with a particular signature region. The spatially averaged radio frequency signatures are calculated as discussed with reference to FIG. **2** and **7**.

When processor **616** has received a request to estimate the location of a subscriber unit, subscriber signature processor **624** recalls data measurements made by channel estimator **612** from storage **614**. These measurements represent radio frequency signature propagation characteristics of a signal from the subscriber unit to be located measured over a plurality of times. Subscriber signature processor **624** computes a time averaged radio frequency signature, as described with reference to FIGS. **4** and **5**.

The process of comparing a time averaged radio frequency signature with a spatially averaged radio frequency signature begins with signature region searcher **626** recalling a spatially averaged radio frequency signature from database **622** for a selected signature region. The output of signature region searcher **626** is coupled to one of the inputs of signature comparator **628**, and another input of signature comparator **628** is coupled to the output of subscriber signature processor **624**. Signature comparator **628** compares the time averaged radio frequency signature of the signal from the subscriber unit to be located and the spatially averaged radio frequency signature of a selected signature region and generates a figure of merit as a result of the comparison. Signature comparator **628** may be coupled to storage **614** in order to temporarily store figures of merit that relate to each signature region recalled by signature region search **626**. Signature comparator **628** may also store the figure of merit and the corresponding signature region in a peak holding manner such that if a higher figure of merit is produced, that figure of merit, along with its signature region coordinates, replace the previous value. Signature comparator **628** is coupled to output function **630**, which formats the subscriber unit's estimated location represented by the signature region with the best figure of merit. This output may be in the form of position coordinates of the signature

region, such as location **46**, or by displaying a map showing the location of the subscriber unit.

It should be noted that the above embodiments have tended to speak to an uplink mode of operation, in which a mobile subscriber unit is the transmitter, and the base transceiver station is the receiver. Alternate combinations of receiver and transmitter are possible in practice, including operation on the downlink. Downlink operation may be achieved by measuring the radio frequency signal propagation characteristics in the subscriber unit, and either computing an associated radio frequency signature in the subscriber unit, or sending the characteristics to the base transceiver for processing to a radio frequency signature. Similar to the uplink methods, this can be done for multiple antennas at the base transceiver.

The foregoing description of a preferred embodiment of the invention has been presented for the purpose of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Obvious modifications or variations are possible in light of the above teachings. The embodiment was chosen and described to provide the best illustration of the principles of the invention and its practical application, and to enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the invention as determined by the appended claims when interpreted in accordance with the breadth to which they are fairly, legally, and equitably entitled.

What is claimed is:

1. A method for creating a radio frequency signature for a signature region in a coverage area of a wireless communication system, the method comprising the steps of:

measuring radio frequency signal propagation characteristics associated with a signal transmitted from a plurality of locations in the coverage area of the wireless communication system;

defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics;

for a selected signature region, processing the selected measured radio frequency signal propagation characteristics within the selected signature region to produce a spatially averaged radio frequency signature for the selected signature region, wherein the processing extracts the dominant features of the radio frequency signal propagation characteristics of a signal transmitted within the selected signature region; and

recording an association between the spatially averaged radio frequency signature and the selected signature region.

2. The method for creating a radio frequency signature according to claim **1** wherein the step of defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics further includes defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics, wherein the signature regions are adjacent to each other, and are geometrically similar in shape and size.

3. The method for creating a radio frequency signature according to claim **1** wherein the step of processing the selected measured radio frequency signal propagation characteristics within the selected signature region to produce a spatially averaged radio frequency signature for the selected signature region further includes decomposing a structured matrix containing vector representations of the signal propagation characteristics within the selected signature region to extract a subspace that represents the dominant features of the radio frequency signal propagation characteristics in the selected signature region.

4. The method for creating a radio frequency signature according to claim **3** wherein the step of decomposing a structured matrix containing vector representations of the signal propagation characteristics further includes the steps of:

performing an eigendecomposition on the structured matrix containing vector representations of the signal propagation characteristics to produce a plurality of eigenvectors and their corresponding eigenvalues; and

selecting N of the eigenvectors that correspond to the N largest eigenvalues.

5. The method for creating a radio frequency signature according to claim **1** wherein the step of measuring radio frequency signal propagation characteristics associated with a signal transmitted from a plurality of locations in the coverage area of the wireless communication system further includes measuring radio frequency signal propagation characteristics in the form of an impulse response for a plurality of locations in the coverage area of the wireless communication system.

6. The method for creating a radio frequency signature according to claim **5** wherein the step of implicitly measuring radio frequency signal propagation characteristics of an impulse response for a plurality of locations in the coverage area further includes measuring a power delay profile for a plurality of locations in the coverage area of the wireless communication system.

7. A system for creating a radio frequency signature for a signature region in a coverage area of a wireless communication system comprising:

means for measuring radio frequency signal propagation characteristics associated with a signal transmitted from a plurality of locations in the coverage area of the wireless communication system;

means for defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics;

means for processing the selected measured radio frequency signal propagation characteristics within a selected signature region to produce a spatially averaged radio frequency signature for the selected signature region, wherein the processing extracts the dominant features of the radio frequency signal propagation characteristics of a signal transmitted within the selected signature region; and

means for recording an association between the spatially averaged radio frequency signature and the selected signature region.

8. The system for creating a radio frequency signature according to claim **7** wherein the means for defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics further includes means for defining a plurality of signature regions in the coverage area that contain selected locations having selected measured radio frequency signal propagation characteristics, wherein the signature regions are adjacent to each other, and are geometrically similar in shape and size.

9. The system for creating a radio frequency signature according to claim 7 wherein the means for processing the selected measured radio frequency signal propagation characteristics within the selected signature region to produce a spatially averaged radio frequency signature for the selected signature region further includes means for decomposing a structured matrix containing vector representations of the signal propagation characteristics within the selected signature region to extract a subspace that represents the dominant features of the radio frequency signal propagation characteristics in the selected signature region.

10. The system for creating a radio frequency signature according to claim 9 wherein the means for decomposing a structured matrix containing vector representations of the signal propagation characteristics further includes:

means for performing an eigendecomposition on the structured matrix containing vector representations of the signal propagation characteristics to produce a plurality of eigenvectors and their corresponding eigenvalues; and

means for selecting N of the eigenvectors that correspond to the N largest eigenvalues.

11. The system for creating a radio frequency signature according to claim 7 wherein the means for measuring radio frequency signal propagation characteristics associated with a signal transmitted from a plurality of locations in the coverage area of the wireless communication system further includes means for measuring radio frequency signal propagation characteristics in the form of an impulse response for a plurality of locations in the coverage area of the wireless communication system.

12. The system for creating a radio frequency signature according to claim 11 wherein the means for implicitly measuring radio frequency signal propagation characteristics of an impulse response for a plurality of locations in the coverage area further includes means for measuring a power delay profile for a plurality of locations in the coverage area of the wireless communication system.

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